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Study of the validity and reliability of the Rastronics CCI-10| With emphasis on probe tube placement and the effects of Select-A-Vents

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A STUDY OF THE VALIDITY AND RELIABILITY OF THE RASTRONICS CCI-10; WITH EMPHASIS ON PROBE TUBE PLACEMENT AND THE EFFECTS OF SELECT-A- VENTS

By

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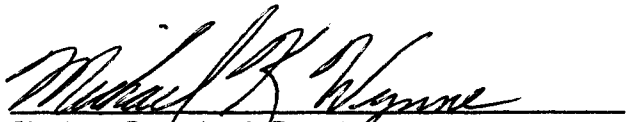

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CHAPTER I: INTRODUCTION

The idea of measuring sound pressure level (SPL) in the ear canal has been in existence for at least 40 years. Wiener and Ross (1946) used a probe tube microphone system to describe the changes in SPL that occur as sound field measurements are obtained as the probe tube is placed closer to the eardrum. They further demonstrated that the presence of the small probe tube in the ear canal did not significantly alter the measured SPL of the signal. These findings have provided the groundwork for continued research on ear canal measurements.

Applications for the use of ear canal measurements have been considered as a potential method for the selection and fitting of hearing aids. Currently, there is little agreement in the literature regarding a preferred method of hearing aid selection, and there appears to be no substantial evidence which would indicate the superiority of any one method. A variety of techniques and procedures has been proposed over the years as a means for selecting amplification.

One commonly used method is the comparative approach described by Carhart (1946). This involves preselecting several hearing aids following the audiologic evaluation. The different hearing aids are then each tested on the individual using a particular stimuli (such as speech recognition tasks). Comparisons between the hearing aids are based upon the improvement noted in test results. According to Walden et.al (1983) several assumptions underlie this type of approach.

These are:

(a) significant differences exist between hearing aids and are reflected on test performance.

(b) differences among aids will vary among patients.

(c) performance differences among aids can be measured reliably by a selected test stimuli.

(d) the performance for a group of hearing aids remains stable over time.

(e) the patient's clinical test situation will reflect the performance of the hearing aid in day to day situations.

However, according to these authors, these basic assumptions may not always be accurate. They reported that when hearing aids with similar electroacoustic characteristics are tested, significant differences in performance will not be observed. Also, the test-retest reliability of the commonly used monosyllabic word lists may not be sufficient to demonstrate inter aid differences. Finally, they indicated that the hearing aid that resulted in the best performance clinically was not always the one judged most beneficial in daily living when used on a home trial basis. Walden et.al (1983) concluded that these assumptions must be further tested by clinicians if they are going to use a comparative approach to hearing aid selection.

Another type of hearing aid selection method is the prescriptive approach. One such approach has been referred to as the half-gain rule, which was recommended by Berger (1976). These types of approaches have an advantage in that they are less time consuming and have greater uniformity between clinicians. However, the basic

prescriptive formula is derived from measurements initially obtained in metal couplers. These and other methods used in amplification selection have been reviewed by Schmitz (1980).

Libby (1984) has maintained that the use of any single hearing aid selection procedure lacks the support of scientific evidence, and that the major reason for lack of progress in hearing aid selection procedures is that the true frequency response of a hearing aid, as perceived by the wearer, has been almost ignored. A major contributor to this problem is the fact that the measurement of the electroacoustic characteristics of the hearing aid has traditionally been done in hard walled metal couplers. Numerous investigators have observed significant differences between coupler measurements and real ear measurements of hearing aid performance. (Ewertson, Ipsen, and Nielsen, 1957; Preves, 1977; Studebaker, Cox, and Wark, 1978; Studebaker and Zachman, 1970; Burkhard and Sach, 1977). Based upon the discrepencies observed between measurement techniques, it would appear that coupler measurements may not be adequate for estimating hearing aid performance.

The procedures and instrumentation used for obtaining ear canal SPL measurements have, until recently, been confined to laboratory research. Libby (1984) cites two reasons for this lack of clinical implementation: (a) the need for an anechoic chamber in order to obtain accurate ear canal measurements and (b) the clinician lacks a convienient microphone system for ear canal measurements. Manufacturers of the Rastronics CCI-10 Frequency Response Analyzer (CCI-10) claim to have overcome both of these obstacles to routine

clinical use.

The CCI-10 consists of the following components (as described by the manufacturer): a sound pressure level monitoring (reference) microphone, a probe microphone with a flexible silicone tube contained in a single assembly, a high performance compressor, a video monitor, a loudspeaker and a printer. The equipment specifications provided by the manufacturer are located in Appendix A. This equipment is available commercially and is purported to be suitable for selection and fitting of hearing aids, including measurements of acoustic modifications such as vents, dampers and various earmold configurations.

The accuracy of the measurements obtained on the CCI-10 have not yet been investigated in detail, despite the manufacturer's claims that it could be used in clinical settings. The purpose of this paper was to investigate three main issues. The first purpose was to determine the accuracy of the instrument. The second purpose was to determine whether probe tube placement location (between the earmold and ear canal or inserted through a special vent in the earmold) would have an effect on the measurements obtained. The final purpose was to determine whether the CCI-10 could measure small acoustical changes in hearing aid insertion gain when different sizes of Select-A-Vent plugs were inserted.

CHAPTER II: REVIEW OF LITERATURE

Amplification System

The traditional behind-the-ear (BTE) hearing aid is coupled to the ear by means of an earmold. The primary purpose of the earmold is to conduct the amplified sound into the ear canal toward the tympanic membrane.

Cox (1979) described the usual components of the total BTE hearing aid coupling system as being: an earmold, 40-45 mm of tubing, an earhook attached to the nozzle of a hearing aid, 8-10 mm of flexible rubber tubing inside the hearing aid which couples the receiver outlet to the nozzle, and an air filled cavity in front of the receiver diaphragm. When measuring the acoustic performance of a hearing aid, the coupling system in combination with the hearing aid must be considered. Although the increasingly popular in-the-ear (ITE) hearing aids have eliminated many of the traditional components, the entire amplification system as worn by the individual user must still be considered. Traditionally, the electroacoustic measurement methods which estimated the performance of a hearing aid have included the hearing aid but have failed to account for all aspects of the coupling system and the individual wearer.

Coupler Measurements

A hearing aid's electroacoustic characteristics have traditionally been measured in hard walled metal couplers, referred to as the 2 cc coupler. The 2 cc coupler was developed to provide a reproducible method of measuring hearing aid output, primarily for purposes of inter-hearing aid comparisons and quality control. This

coupler, which is still the standard measurement of electroacoustic characteristics specified by ANSI (S 3.22-1982), was designed on the premise that there is approximately 2 cc of air volume remaining in the adult external auditory meatus with an occluding earmold in place. According to Cox (1979), 1.5 cc (rather than 2 cc) is a closer estimate to the actual remaining volume of air with the occluding earmold in place. The 2 cc coupler was not intended to match the impedence of the external auditory canal or the eardrum.

Although the 2 cc coupler was not originally intended as a means of predicting hearing aid performance on individual users, the frequency response curves are often used by clinicians in the hearing aid selection procedure as a means of predicting hearing aid performance for the individual. However, research results have demonstrated significant differences in electroacoustic output when measurements obtained on a 2 cc coupler have been compared to those obtained on real ears. Therefore, the practice of clinicians of relying on the frequency response curves obtained in a 2 cc coupler may be an inaccurate assessment of individual hearing aid gain while being worn.

McDonald and Studebaker (1970) compared SPL measurements obtained on a 2 cc coupler to ear canal probe microphone measurements while varying earmold configurations. The four different earmold configurations consisdered were representative of general clinical practice:

1) a standard occluding earmold,

2) an earmold with a shortened canal and hollow concha section,

3) an earmold with a shortened canal, hollow concha section and vented.

4) an open earmold.

When the standard earmold was used, the probe microphone results showed a 7-8 dB rise in SPL for frequencies above 1000 Hz when compared to the 2 cc coupler results. Differences in SPL between the two measurement methods were no greater than 2.8 dB for frequencies up to 800 Hz, which indicated a good agreement between those methods for the low frequencies. The probe microphone measurements with the vented and open earmold showed considerable reductions in the low frequency region as compared to the measurements with the occluded earmold. The implications of these results demonstrated the necessity to consider the entire amplification system including all earmold modifications during the hearing aid evaluation as oppossed to relying on only the frequency response curves of the hearing aid as measured in a 2 cc coupler.

Studebaker and Zachman (1970) also reported higher SPL measured in real ears, often as much as 5-7 dB in the higher frequencies, when compared to the 2 cc coupler measurements. McDonald and Studebaker (1970) have cited other researchers who have observed this increase in measured SPL in real ears when also compared to the 2 cc coupler measurements. Nicholas (cited in McDonald and Studebaker, 1970) noted a 5-7 dB increase at frequencies above 1000 Hz and Van Eysberger and Groen (cited in McDonald and Studebaker 1970) reported a similiar trend with differences as great as 20 dB at 4000 Hz when the two methods were compared. Killion (1981) suggested that even when custom

earmolds have been measured on the HA-1 coupler, a rough rule of thumb was to expect a higher SPL in real ears of 3.5 dB in the low frequencies, 5 dB at 1000 Hz, 10 dB at 3000 Hz and 15 dB at 6000 Hz. These recommendations do not take into account the opposite findings reported by Ewertsen, Ipsen, and Neilsen (1957). They compared ear canal measurements to 2 cc coupler measurements and reported an increase in the measured SPL at frequencies above 2000 Hz for the coupler's response rather than a decrease in the measured SPL.

Despite the important function of inspection control performed by the 2 cc coupler, Lybarger (cited in Staab, 1978) has enumerated several drawbacks of this device:

1) Due to the stiff walls and little or no acoustic resistance in the 2 cc cavity, the hearing aid response curves may show considerably sharper curves than those observed in real ears.
2) The SPL in real ears is generally higher over a large frequency band than that measured in the 2 cc coupler, suggesting that the volume of the 2 cc coupler may be larger than desirable.
3) The shape of the cavity within the 2 cc coupler is different from real ear canal shapes and, consequently, it is not adequate for open canal measurements.

Due to the inadequacies of the 2 cc coupler, the Zwislocki coupler was developed to more closely approximate the impedance of an ear canal. The volume of the Zwislocki coupler when occluded is roughly 1.2 cc as compared to the 2 cc volume of the standard 2 cc coupler. The Zwislocki coupler also has four resonant cavities which

were designed to comprise the inertance, resistance and compliance of the ear canal (Pollack,1980).

Studebaker, Cox, and Wark (1978) compared 2 cc coupler, Zwislocki coupler, threshold, and probe tube microphone measurements on standard, vented, and open earmolds. The measurements obtained on the Zwislocki coupler showed that the vent associated resonance was significantly more damped than that on the 2 cc coupler, but was not as damped as those obtained from real ear measures. Studebaker et al., (1978) noted that the Zwislocki measurement results more closely approximated the real ear results than did the 2 cc coupler, but that notable differences between the real ear and Zwislocki measurements were still present. Some of these differences may have been due to the tighter seal of the earmold to the coupler than that on a real ear. The acoustic leakage allowed by the seal in real ears resulted in a damped frequency response and a less steep low-frequency slope.

Although the Zwislocki coupler more closely approximated the characteristics of the ear canal, it did not account for the effect of head and body diffraction. In order to more closely simulate real life conditions, some research have included measurement with manikin heads without torso, most of which did not attempt to duplicate the ear canal transmission characteristics. However, the Knowles Electronic Manikin for Acoustic Research (KEMAR) was equipped with a Zwislocki coupler and was intended to provide more lifelike test conditions. Berland (1982) described the basic set up in an anechoic chamber for obtaining "simulated in situ" while those obtained on human subjects was referred to as "in situ". The differences in

nomenclature have resulted in some confusion as to the interpretation of the hearing aid's response. For example, according to Hawkins and Schum (1984), the manufacturer's specification sheets on hearing aid electroacoustic characteristics may include:

a) 2 cc coupler gain

b) Zwislocki coupler gain

c) Zwislocki coupler mounted in KEMAR (referred to as "in situ")

d) "in situ" minus the free field to eardrum transfer function or "insertion gain".

The assumption that the "in situ" gain measure provides an approximation closer to real ear gain simply because it is a measurement obtained with a Zwislocki coupler on a KEMAR may result in an over estimation of functional gain by as much as 15-20 dB. Hawkins and Schum (1984) recommended that the use of the "insertion gain" measure will provide the closest approximation of functional gain, but even so, differences in gain estimates will still exist.

The clinical reliance on the technical specification sheets may also be misrepresentative of the hearing aid's characteristics because the data sheets provided by the manufacturer are frequently an indication of the electroacoustic characteristics of the particular model of the hearing aid and not of that particular hearing aid. Pollack (1980) reported that individual hearing aids of a specific model may vary as much as 10-15 dB in gain.

Real Ear Measurements

Until recently, ear canal measurements have been restricted to research projects rather than having been adopted for clinical use.

This was partly due to the necessity of obtaining measurements in an anechoic chamber in order to insure the reliability of the responses. Several researchers have described numerous attempts to obtain reliable measures. For example, Studebaker and Zachman (1970) used an elaborate floor mounting device to hold the microphone assembly in place. Because of the variability noted in their results, McDonald and Studebaker (1970) altered the mounting device and used a head borne helmet which connected to the probe microphone assembly. They also designed special earmolds with a small arm which extended into the ear canal for the placement of the probe tube. Gilman and Dirks (1984) described a probe earmold system in which the probe is built into the earmold and does not extend into the ear canal any further than the earmold itself. This system provides the examiner with a precise location of the probe tube and made repeated measurements more reliable.

Changes in SPL are also known to occur when measurements are obtained closer to the eardrum. Weirner and Ross (1946) used a probe microphone placed at three different locations in the ear canal and demonstrated a 17-22 dB gain in SPL as the location of the microphone progressed from the free field to the eardrum at 3000 Hz. They concluded that this increase in gain was due to the resonance of the auditory canal and the combined effects of diffraction by the head and pinna.

Recently, Pedersen, Lauridsen, and Nielsen (1982) used a specially devised probe tube microphone system and obtained ear canal measurements on KEMAR at three different probe tube tip locations.

According to these researchers, when sound was measured in an open ear canal, there were no changes in SPL for frequencies below 4000 Hz until the probe tip was removed to approximately 15 mm from the eardrum. For the closed ear canal condition, they observed a reduction in SPL when the probe tip was removed to roughly 10 mm from the eardrum.

Hawkins and Mueller (1986) compared measurements of three different probe tube locations, (1, 5, and 10 mm past the end of the earmold simlulator). They noted that the accuracy of the output diminished substantially above 2500 Hz when the probe was inserted only 1 mm beyond the tip of the earmold simulator. Based upon their results, they recommended that the placement location be one-half the distance from the tip of the earmold to the eardrum. They also recommended that care should be taken to maintain a constant placement location for unaided and aided measurements. Currently, other data regarding the effects of probe tube insertion depth on real ears with the CCI-10 has not been available. The manufacturer has recommended that the probe tube extend to 2 mm beyond the earmold tip, however the adequacy of this placement versus a placement closer to the eardrum has not been thoroughly investigated. Previous investigators have described other concerns such as the immobilization of the probe assembly, the precise seating and location of the subject, and the acoustics of the test room environment. These issues have not yet been adequately addressed to insure clinical reliability of the CCI-10.

Pedersen et al., (1982) have also compared measurements obtained with a miniature microphone such as that used by Harford (1980) to

those obtained with a probe tube microphone on KEMAR. The results from both the probe tube and probe microphone measurements were determined to correspond closely with the results obtained from the KEMAR microphone measurements. This implied that either probe measurement method yielded results which were similar to those expected from KEMAR measurements. These authors indicated that they preferred the probe tube microphone as they thought it was easier to insert and it offered less risk of injury to the patient. Also, they claimed that an accurate placement was less important with the probe tube microphone than with the miniature microphone, which was placed according to procedures as described by Harford. An additional finding reported by Pedersen et. al. (1982) was that the ear canal measurements demonstrated a reduction in hearing aid insertion gain above 2000 Hz rather than an increase in the insertion gain as had been previously reported.

Lauridsen and Neilsen (1981) obtained insertion gain measurements on six subjects with a probe tube microphone similar to that described by Pedersen et al., (1982). Three different hearing aids with the same earmold were measured. Their results showed that different hearing aids on the same individual with the same earmold did not produce a variety of insertion gain curves as was expected. Rather, their results indicated that the upper limiting frequency (the highest frequency to demonstrate an increased insertion gain) was essentially independent of the hearing aids tested. The clinical and research ramifications of these findings on the continued search to improve and extend high frequency amplification is significant. These results

indicate that the amount of high frequency gain that is delivered by a hearing aid may not be significantly different across different hearing aids. Lauridsen et al., (1981) suggested that the lack of differences in insertion gain question the validity of a comparative approach to hearing aid fitting. A second finding of this study was that even though the insertion gain could be altered with earmold modifications, the effects of these modifications were not as great as desired. Still, it should be noted that wideband hearing aids were used in this study, and therefore, conclusions can not be drawn regarding other types of hearing aids such as high pass hearing aids.

Ringdahl, Leijon, Liden, and Brackelin (1984) obtained ear canal measurements on three different high pass hearing aids on fourteen different subjects. They noted only occasional large differences in the frequency response of the hearing aids. However, they suggested that the impact of the small differences in hearing aid performance observed in their study needed to be further investigated. Manufacturers of the CCI-10 have claimed that this instrument has the capacity to measure relatively small differences in hearing aid output although this has not been adequately demonstrated in the literature.

Rastronics CCI-10

According to Pedersen et al., (1982) the requirements for a hearing aid measurement instrument that would be suitable for routine clinical use would include:

1) Easy placement in the ear canal.

2) No notable risk of damage to the tympanic membrane (i.e. insertion by nonmedical personnel should be possible following

an otologic examination).

3) The recording of the results must be possible during the hearing aid evaluation appointment.

4) Measurements must be obtained in a reasonable time period.

These criteria formed the basic groundwork for the development of the Rastronics CCI-10 . The manufacturers of the CCI-10 have suggested that the CCI-10 could provide clinically useful information during the hearing aid selection and fitting procedures. There is, however, limited research avalible comparing the effectiveness of this procedure to other procedures.

Mason and Popelka (1985) compared measurements of insertion gain obtained on the CCI-10 to functional gain measurements on 12 subjects with hearing aids. Standard deviations of less than 5 dB were observed between probe tube and functional gain measures across all frequencies measured between 250 and 4000 Hz, with the exception of 1500 Hz. These authors concluded that their results were essentially equivalent with either method. In addition, both methods exhibited an advantage over 2 cc coupler gain measurements in that they accounted for the individual's ear geometry and acoustic differences as well as for the differences due to the hearing aid coupling system. Furthermore, the probe tube measurement system did not rely on threshold measurements, which are known to vary both within and across subjects, thereby making them a more reliable method of measuring the gain of a hearing aid. Another advantage of the probe tube system was the amount of time saved compared to the amount of time required to obtain functional gain measures. The authors advised that at least

one of the two methods should be used when fitting a hearing aid. Despite the advantages of a probe tube system, these authors stated that, from a practical standpoint, functional gain measures should now be obtained routinely. Currently, most clinics appear to have the facilities to conduct these measures and are currently applying them in their hearing aid evaluations.

Jablin (1984) compared the measurements obtained on a 2 cc coupler, the estimated insertion gain based on KEMAR correction factors, and the insertion gain as measured by the CCI-10 for a behind-the-ear, in-the-ear and canal style hearing aid. Ear canal measurements were obtained on only one subject. She noted that there was disparity between the three measurements for each style of hearing aid. According to Jablin, if the selection of amplification had been based upon coupler or estimated insertion gain measurements, the appropriate hearing aid would not have been selected. Subjective judgements made by the subject and the examiner (using the monitor headphones) described the signal at approximately 2000 Hz for the behind-the-ear hearing aid and at approximately 3000 Hz for the in-the-ear hearing aid as being "harsh, raspy" and "muddy". According to Jablin's interpretation, the frequency response curve obtained on the CCI-10 contained notable peaks and valleys at those same frequencies. However, the canal hearing aid was described as being a smooth broad band response and was subjectively judged as being "pleasant". She did not provide any details which described how these judgements were made. One might conclude that this subject may have been successful at selecting the most appropriate hearing aid regardless of the

measurement technique. Still, Jablin pointed out that for the behind-the-ear hearing aid measurements, the presence of the earmold created a maximum insertion loss at the same frequencies at which the subject's ear canal resonance was greatest. An examination of the three ear canal resonance curves obtained (for the same subject) showed considerable differences in the frequency response curves. If this resonance curve is to provide diagnostic information (which is a claim of the manufacturer) one should expect to see less intra-subject variability. Clearly, the importance of the ear canal resonance measure will require further investigation before this technique can be adopted clinically with sufficient confidence.

During a panel discussion, Preves ("Measuring Performance", 1985) commented that the usefulness of the ear canal resonance measure remains uncertain. The exact relationship between the ear canal resonance with the final hearing aid fitting is unclear. One reason for its limited application is that sound must ultimately travel beyond the ear canal and through the middle ear system. Larson and Talbott (1983) have also investigated the effect of static middle ear pressure differences on ear canal SPL measurements. Even when small differences were noted between the ear canal pressure and the middle ear pressure, significant differences in ear canal SPL measurements were observed. These authors concluded that it may be necessary to monitor ear canal pressure when an ear canal measurement procedure of hearing aid gain is used because of the variable effects due to middle ear pressure changes Furthermore, the fluctuating nature of middle ear pressure in young children may limit the utility of these types of

measurements in this population.

Harford's Probe Microphone

A second type of ear canal measurement device that has had limited clinical use is the probe tube microphone system that has been described by Harford (1980). This instrument has been incorported into the routine clinical hearing aid selection procedures at the University of Minnesota's audiology clinic. The use of this device in both hearing aid fitting and follow-up porcedures was described by Harford (1984). He cited that a major drawback to his procedure was the lack of standardized instrumentation and procedures for exchange of information. (This has been a similar drawback of the CCI-10 as cited by Mason and Popelka, 1985). Despite other drawbacks, including the limitation to test frequencies under 5000 Hz, the occasional feedback due to the presence of the microphone, and the limited research or clinical application reported, Harford has found the device to be useful in a variety of ways. According to Harford the probe microphone device has been used to determine the following:

1) The hearing aid's frequency response.

2) The real ear SSPL 90.

3) Differences between "use" and "full on" gain.

4) The quality of the frequency response.

5) The effects of electroacoustic and acoustic modifications.

6) Comparisons of one hearing aid to another.

7) Binaural matching of the hearing aids.

Recently, Ringdahl and Leijon (1984) investigated the reliability of ear canal measurements with an ear canal microphone and a probe

tube microphone. They observed less than a 4 dB difference between 250 and 4000 Hz between the two canal style measurements. However, they did observe a 7-10 dB difference at 5000 and 6000 Hz . These authors then varied some of the potential sources of error such as subject's head position, presence of the probe tube, and changes in the location of the probe tube and microphone. They did not note any significant effect on the measurements during changes in the above conditions. They concluded that either method was appropriate for clinical use; however, for practical reasons they preferred the probe tube procedure.

Functional Gain

Another type of real ear measure is functional gain. Functional gain relies on a behavioral response from the individual and is therefore referred to as a psychophysical measure rather than an acoustical measure. Functional gain has been described by Preves (1984) as the amount that the hearing aid changes the person's hearing threshold levels. Measurements of functional gain are obtained by sound field testing using either speech stimuli or tones for selected frequencies. The subject is tested first without a hearing aid and the results are recorded (these are the subject's unaided results). Then the subject is tested with the hearing aid in place (this is the subject's aided results). A comparison between the unaided and aided condition is then made to determine the amount of functional gain for that subject.

One of the frequently cited advantages of functional gain measures is that it is based upon the subject's response and not upon

a mechanical measurement. However, a disadvantage to this is that the measurement relies upon a subjective response and is dependent upon the capabilities of the individual to respond on a consistent basis. Some of the other potential problems with functional gain measures include possible standing waves in the sound field and the amount of time required to complete the test. The discrepencies between the results from functional gain measurements and from 2 cc coupler measurements have been summarized by Hawkins and Haskell (1982). In general, differences have been reported in both the magnitude and direction of gain for frequencies below 750 Hz. Between 750 Hz and 1500 Hz, the averaged measures indicated that 2 cc coupler gain underestimated functional gain by approximately 10 dB. For the frequencies above 1500 Hz, the results have shown that the coupler gain over-estimated functional gain across all studies, but by varying amounts. Hawkins and Haskell (1982) stated that this variability necessitates that the clinician obtain functional gain measurements on an individual basis rather than strictly relying upon 2 cc coupler measurements.

Mason and Popelka (1985) also compared functional gain to 2 cc coupler measurements and reported significant variability between measurements for frequencies below 750 Hz and above 2000 Hz. These authors strongly supported the need to obtain functional gain measurements during hearing aid evaluations.

Preves (1984) has rated the various hearing aid measurement methods based upon the "level of realism" provided by the particular method. Based upon his review of the literature he has rank ordered

the techniques in the following way:

1. The most realistic technique (most accurate) was functional gain measures.
2. The second most realistic method was probe tube measurements.
3. The third most realistic method was correction factors applied to coupler measurements.
4. The fourth most realistic technique was measurements obtained on KEMAR.
5. The fifth most realistic technique was measurements obtained on Zwislocki couplers.
6. The least accurate measurement technique were those obtained on the 2 cc coupler.

Earmold Vents

Measurements of the effects of Select-A-Vent (SAV) modifications has not been previously reported using the CCI-10. Anticipating the effects of SAV sizes has generally been based upon measurements obtained in hard walled couplers. SAV systems may be used with a parallel vent configuration or with a side branch vent, however, the latter will result in a high frequency transmission loss (Cox 1979). Two aspects which contribute to the overall acoustic effect of the SAV system are the effect of the vent bore and the effect of the insert. Lybarger (1979) compared a short hollow tip earmold to a channel 3.7 mm long and 3 mm in diameter and concluded that the larger diameter inserts have little effect on the acoustic response. Because the vent channel is so much larger than that of the SAV insert, he indicated that it actually is the vent channel controlling the response change

and not the vent plug. Cox (1979) reported the effect of the insert size on the acoustic response measured on an ear simulator using an earmold with a vent bore 13 mm in length beyond the insert and 2.5 mm in diameter. Five distinct, fairly evenly spaced curves, which affected a limited frequency range were evident. Cox reported a change in the vent associated peak resonance at 480 Hz for the smallest diameter insert to 650 Hz for the largest diameter insert. An approximate 10 dB low frequency transmission loss was noted for the largest diameter vent compared to the smallest diameter vent at any given frequency. Lybarger (1978) has prepared tables which the hearing aid specialist may find helpful for use when anticipating effects of SAVs. His findings indicated that the most open plugs (.125", .094" and .062") resulted in the exact response as the open vent condition. Changes in low frequency response were noted for sizes .031" and .020". The amount of low frequency reduction was dependent upon the length and diameter of the vent bore.

Statement of the Problem

A review of the literature indicated that considerable disagreement exists regarding the evaluation of hearing aid output. A variety of differences have been reported between results obtained on various types of mechanical couplers versus those obtained in the ear canal through the use of probe tubes and probe microphones.

The purpose of this paper was to investigate a new computerized probe microphone device which is now avalible for clinical use. The Rastronics CCI-10 has the capacity to obtain ear canal measurements of hearing aid output in approximately two minutes. Clearly, the

advantage of the time saved using real ear measurements compared to functional gain procedures is apparent. Additionally, these measurements are obtained on the individual user versus in a hard walled coupler. However, the accuracy and the reliability of the CCI-10 have not been thoroughly investigated. The intent of this study was to examine some of these issues. Specifically, measurements were obtained to confirm the accuracy of the frequency and the SPL output indicated on the CCI-10. The actual ear canal measurements obtained were intended to compare the two different probe tube insertion locations. The first condition was with the probe tube inserted through a special vent in the earmold. The second condition was with the probe tube inserted between the earmold and the ear canal. The final question investigated was whether small changes in insertion gain would be recorded by the CCI-10 as the different sizes of SAV insert plugs were measured.

CHAPTER III: METHODS

Subjects and Examiners

Two female subjects, both employed in the Audiology Division at the Seattle Veterans Hospital participated in this study. Audiologic criteria required for participation were normal pure tone thresholds (20 dB HL or less at 250, 500, 1,000, 2,000 and 4,000 Hz), and acoustic immittance results within normal limits (normal mobility bilaterally with point of maximum compliance between -200mm to +50mm H20). Otoscopic inspection was conducted to insure adequate ear canals for probe tube insertion.

The two subjects also served as examiners. They were both familiar with the purposes and procedures of this study and each had ample practice with the CCI-10 and probe tube insertion.

Instrumentation

Testing was completed in a standard Industrial Acoustics Company test booth (length 10′, width 8′4", height 6′6"). The Rastronics speaker was suspended so that it was level with the subject′s ear at a 0 azimuth, and was approximately 2′ from the side walls. All other instrumentation was located approximately 2′ from the speaker. The manufacturers of the CCI-10 have not made specific recommendations regarding positioning of equipment, but indicated that testing could take place in any quiet room. See Appendix B for the testing procedures. The calibration curves that were generated throughout the test procedure have also been included in Appendix B.

The Rastronics CCI-10 consists of a self-calibrating probe microphone which is comprised of both an electret reference microphone

and the actual probe microphone, with a 1 mm soft silicone rubber probe tube which is inserted into the ear canal. A high performance compressor generates the sound field signal. Response curves are displayed on the video monitor and hard copies may be obtained on an Epson FX-80 dot-matrix printer.

Equipment

Each subject wore a custom made earmold (Westone Standard #2) with Select-A-Vent (SAV) options. A smaller vent was made to precisely accommodate the probe tube. No attempt was made to control for the length of the canal of the earmold. A mild gain, broad band Telex 337E behind-the-ear hearing aid coupled to the earmold was used for all measurements.

Materials and Procedures

In order to check the reliability of the frequency indicated on the video monitor, a frequency counter (Hewlett Packard 5512 A Electronic Counter) was attached to the Rastronics unit and a pure tone rather than a "warbled" tone was generated. Comparative measurements were made at six different frequencies between that indicated on the frequency counter and that on the CCI-10 video monitor.

An assessment of the accuracy of the 80 dB SPL signal generated by the CCI-10 was accomplished by obtaining SPL measurements on a Bruel and Kjaer sound level meter (Type 1 Model 2218) with a 1/2" microphone situated on a tripod approximately 1 meter from the speaker. The probe microphone assembly for the CCI-10 was 1 to 1 1/2" directly below the sound level meter microphone. The probe tube

assembly was held in the manner recommended by the manufacturer, i.e., holding the probe tip approximately 1/4" from the microphone assembly. Three separate trials were run and SPL measurements were recorded at six different frequencies. A comparison was made between the SPL measured on the sound level meter and the CCI-10 for each of the three trials.

Several different probe tubes were provided with this instrument. In order to determine if the probe tubes could be used interchangeably a frequency response curve was obtained with a clear tube and then an opaque tube. These two frequency response curves were then compared to each other.

All of the actual ear canal measurements were obtained by the procedures recommended by the manufacturer. The second question of this study also investigated whether the probe tube placement location would effect output measurements. The two placement locations were investigated:

1) with the probe tube inserted through a special vent in the earmold, referred to as Condition A.
2) with the probe tube inserted between the ear canal and ear canal. This is referred to as Condition B.

Frequency response curves were obtained for both of these conditions on both subjects.

The final question was whether the CCI-10 could measure small acoustic changes that occur when different SAV plug sizes were inserted. A frequency response curve was obtained with each of the different SAV sizes, including fully occluded and fully unoccluded.

SAV plugs were systematically varied for both subjects for both of the two probe tube placements. The SAV inserts measured were: .125", .094", .062" .031" and .020".

RESULTS

The first question regarding the reliability of the Rastronics CCI-10 was to measure the accuracy of the frequency recorded on the video monitor. Table 1 shows the comparisons made at six different frequencies between the CCI-10 and an independent frequency analyzer.

Measurements obtained between 250 and 2,000 Hz showed fairly good agreement between the CCI-10 and the frequency analyzer. However, a difference of 7 Hz at 3084 Hz and 13 Hz at 4,000 Hz was noted between measurements. This indicated that the CCI-10 accurately generated low to mid frequencies but that it may not be as accurate at the higher frequencies. The significance of these differences was not determined.

Table 1. A comparison of frequency between the Rastronics CCI-10 and an independent frequency analyzer.

CCI-10	Frequency Analyzer
250	250
500	500
1000	1001
2000	2003
3084	3091
4000	4013

Measurements of SPL were made on a sound level meter and were compared to the signal generated and recorded by the CCI-10. The results of the measurements for three separate trials obtained on the CCI-10 are displayed in Figure 1. The results obtained on the sound level meter for the three trials are shown on Figure 2. These results demonstrated that the CCI-10 consistently recorded a SPL of 80 dB

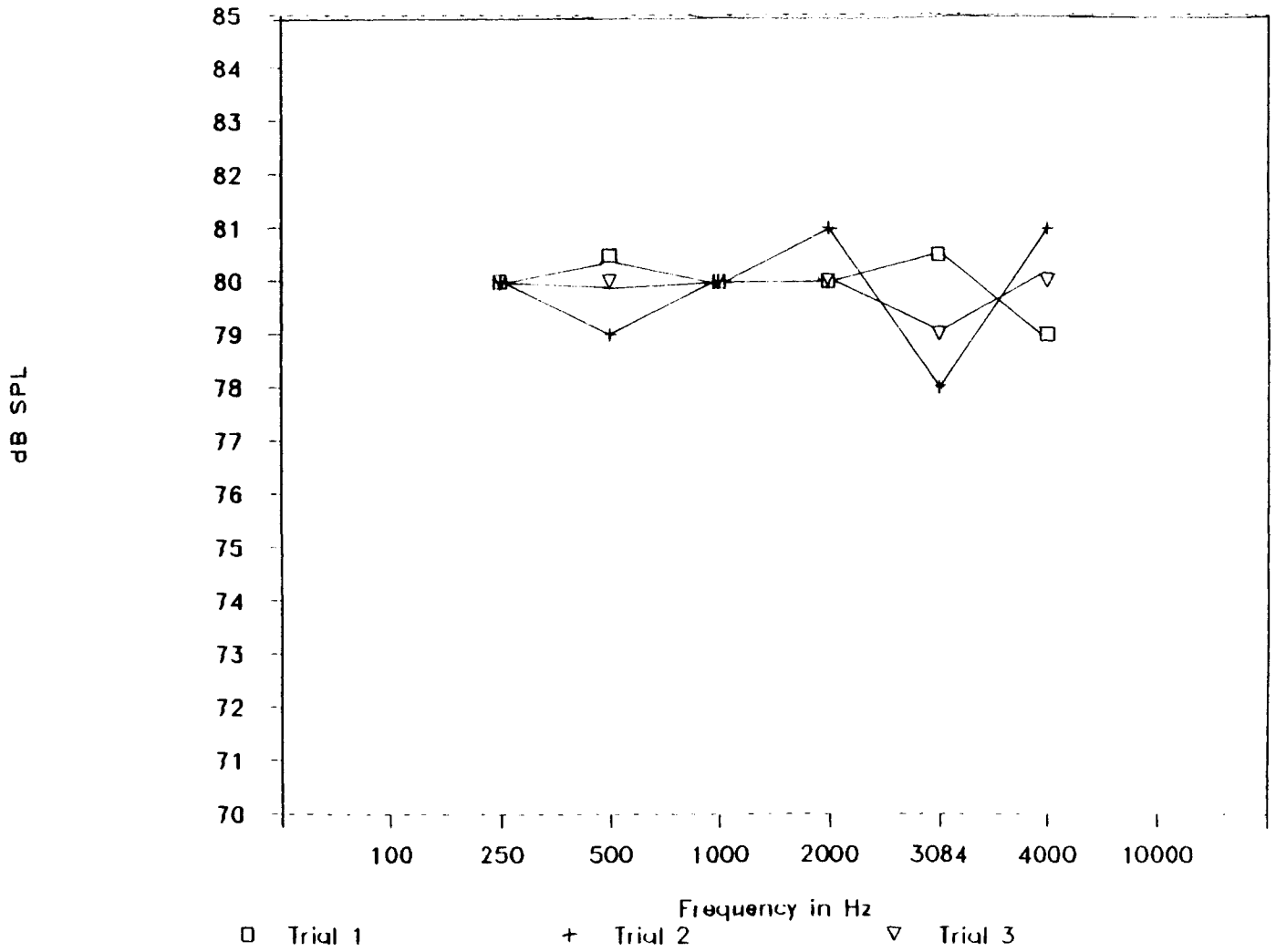

Figure 1. CCI-10 data obtained on three separate trials of the 80 dB (± 1dB) calibrated signal.

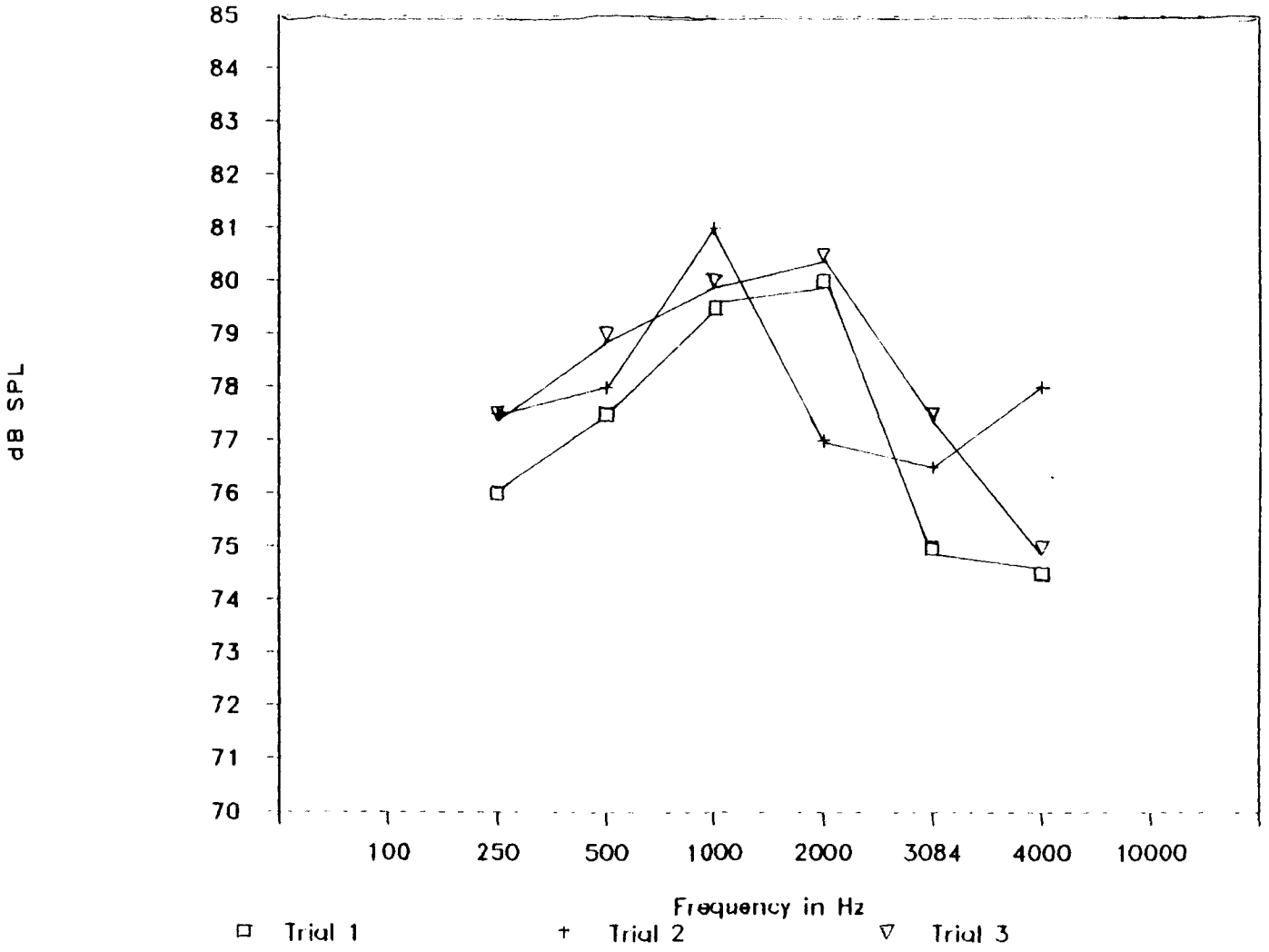

Figure 2. Sound level meter (Bruel and Kjaer) data obtained on three separate trials of the 80 dB (± 1 dB) calibrated signal.

(± 1 dB) throughout the frequency range, with only one exception at 3084 Hz, where a 2 dB difference was recorded. These results also suggested that the CCI-10 was a very reliable instrument for the frequencies measured and that the output was within the manufacturer's specifications.

The SPL measured by the sound level meter showed greater variability for the three trials and typically measured less SPL than that recorded on the CCI-10. Therefore, although the CCI-10 recorded a consistent SPL, the sound level meter readings were more variable than those obtained by the CCI-10. Figure 3 shows the differences in measurements between the CCI-10 and the sound level meter. Differences of 4 dB at 250 and 2000 Hz and 5 dB at 3084 Hz were observed on separate trials. In fact, 1000 Hz was the only frequency where both instruments measured an 80 dB (± 1 dB) signal for all three of the trials.

In order to determine small acoustic changes in hearing aid output, it is important to know the exact SPL being generated by the instrument. The results of this preliminary measurement suggested that the CCI-10 did not accurately and consistently produce an 80 dB (± 1 dB) signal at any frequency except 1000 Hz when measured on the sound level meter.

In summary the results based upon recordings by the CCI-10 alone suggested that the CCI-10 is a highly reliable instrument. However, when compared to independent sound level measurements, several inconsistencies were observed which were not reflected on the CCI-10. The exact manner in which these findings would effect the ear canal

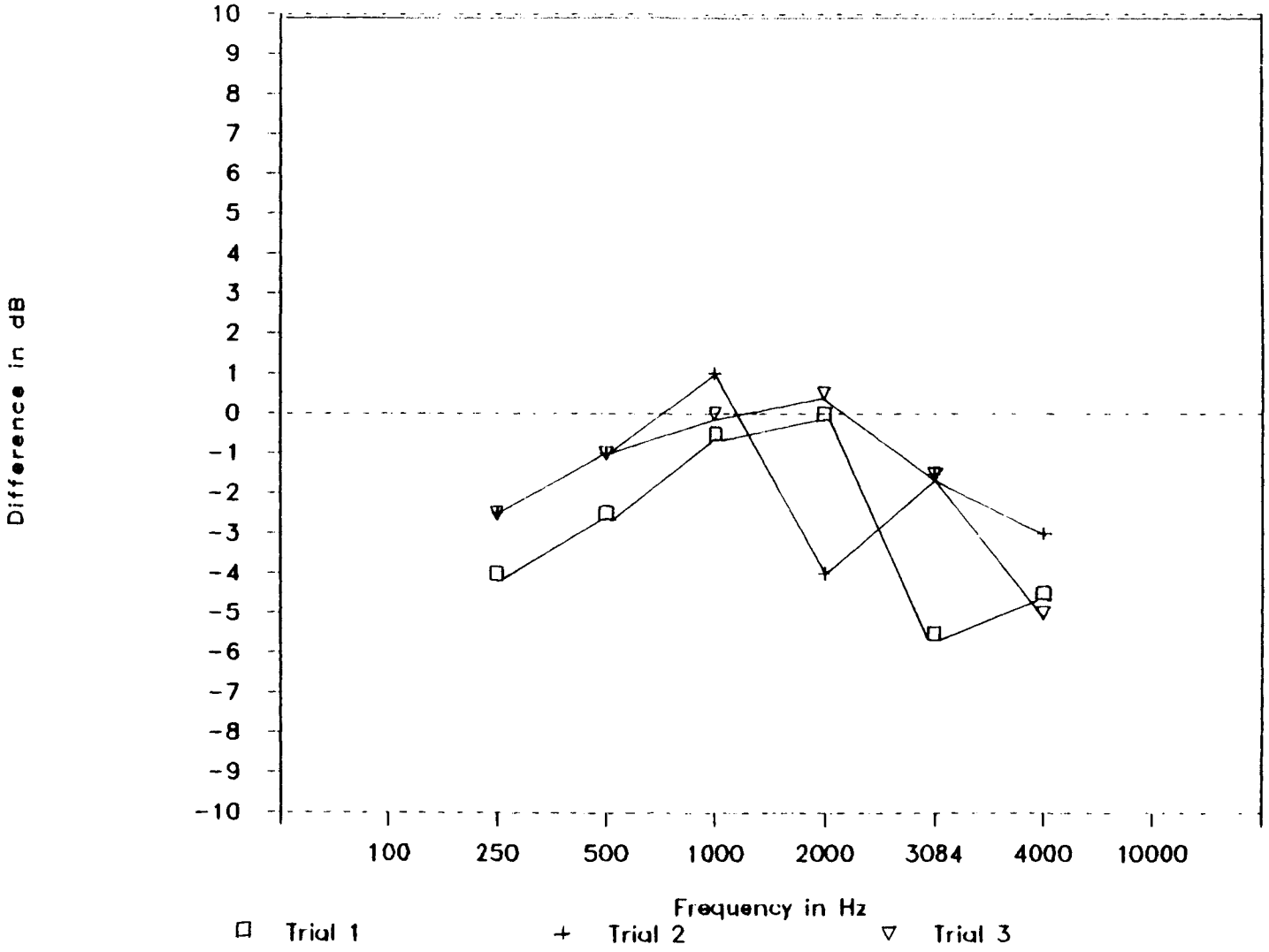

Figure 3. Differences in dB between the CCI-10 and the sound level meter. Negative data points indicate trials in which the sound level meter readings were less than the CCI-10.

measurements on the subjects was not known.

When two different probe tubes were compared to determine the interchangeability of probe tubes, the frequency response curves were similar through 500 Hz. For the frequencies above 500 Hz, the differences ranged from 2 dB to 6 dB, with the greatest difference occuring at 2000 Hz. Figure 4 shows the frequency response curves obtained on two different probe tubes. The results demonstrated that the different probe tubes may have some effect on measurements at some specific frequencies.

The results displayed on Figure 5 were obtained on subject 1 with the probe tube inserted through the special vent in the earmold. The insertion gain for each of the various select-a-vent (SAV) insert plug sizes, including a completely open and a completely occluded earmold have been plotted. The results for this subject showed that the insertion gain at 250, 500, and 749 Hz gradually increased as the SAV size was reduced. However, when the occluded condition was measured, a reduction in the insertion gain in these same frequencies was noted. This outcome contradicted the original hypothesis that the insertion gain would gradually increase as the SAV size decreased. Of the eight frequencies measured, 5 showed a reduction in insertion gain for the occluded earmold condition compared to the open vent condition.

The results for subject 1 with the probe tube inserted between the earmold and ear canal are shown in Figure 6. These results showed considerably less variability between measurements and demonstrated a small increase in the insertion gain for 250 and 500 Hz as the measurements progressed from the open to the occluded earmold. An

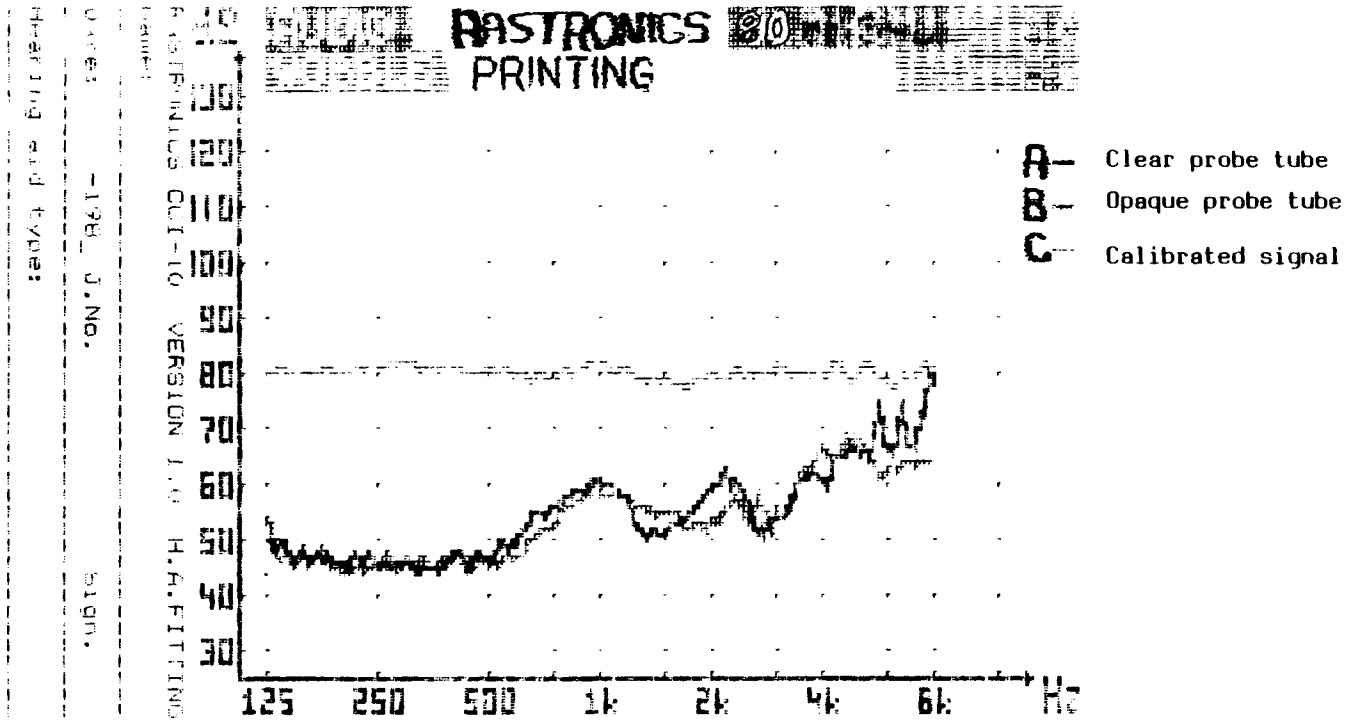

Figure 4. Frequency response curves obtained using 2 different probe tubes. This measurement was made outside of the ear canal after the 80 dB signal was generated.

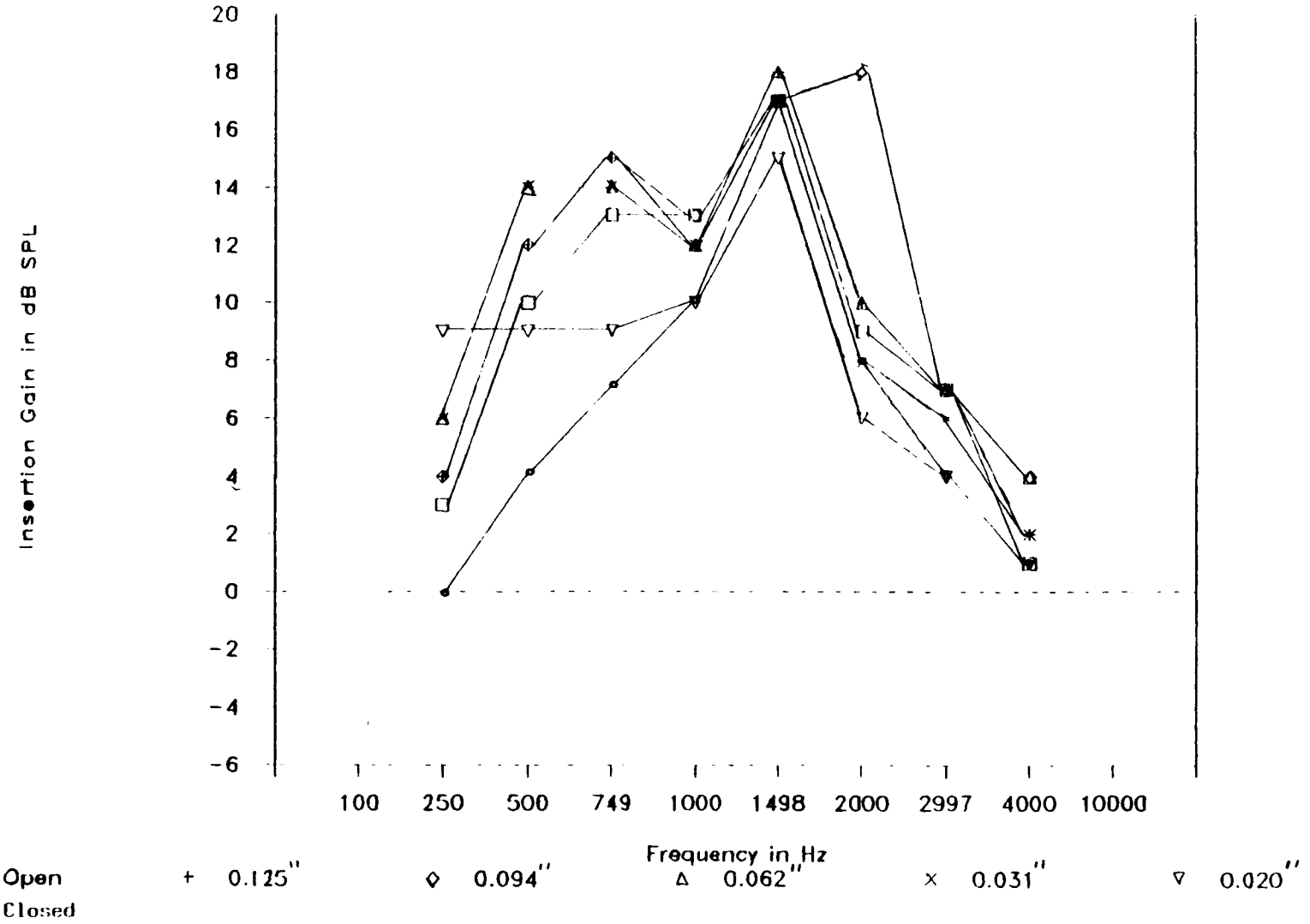

Figure 5. Insertion gain measured for subject 1 for each SAV size with the probe inserted through special vent.

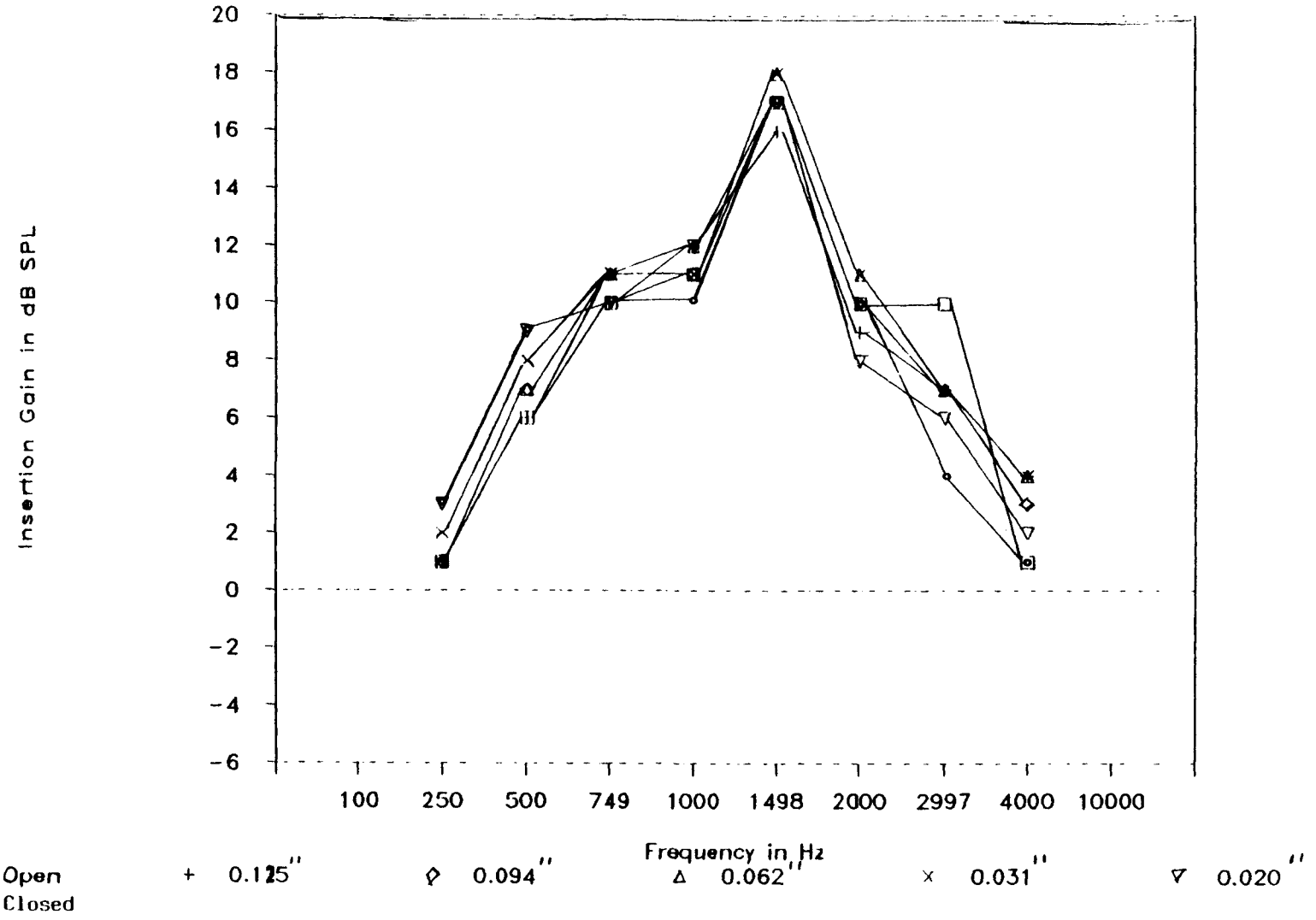

Figure 6. Insertion gain measured for subject 1 for each SAV size with the probe between earmold and ear canal.

exception was noted at 2997 Hz, where a 6 dB reduction in insertion gain for the occluded earmold was measured. All of the other mid to high frequencies remained essentially unchanged regardless of the SAV size. These results were more consistent with the hypothesis that a gradual increase in insertion gain for the lower frequencies would be measured as the vent became more occluded.

A comparison between measurements obtained with the probe tube through the special vent and the probe tube between the earmold and ear canal for subject 1 is shown in Figure 7. Typically, more insertion gain (up to 7 dB) was measured throughout the lower frequency region for all SAV plug sizes except the occluded earmold condition when the probe tube was inserted through the special vent. However, in the mid to high frequency range, greater gain was most frequently recorded when the probe was placed between the earmold and ear canal, still, these differences were no greater than 3 dB.

In summary, it would appear that the most consistent measurements were obtained when the probe tube was placed between the earmold and ear canal. When the probe tube was inserted through the special vent, the variability between measurements increased. Also, the measurements obtained when the SAV was occluded were the opposite of the expected findings. For this subject, equivalent results were not obtained when the two probe tube placements were compared. The greatest differences occurred in the lower frequency region. This variability, coupled with the variability noted when the sound level measurements were taken, obscure the interpretation of specific acoustic effects caused from changes in SAV insert plugs.

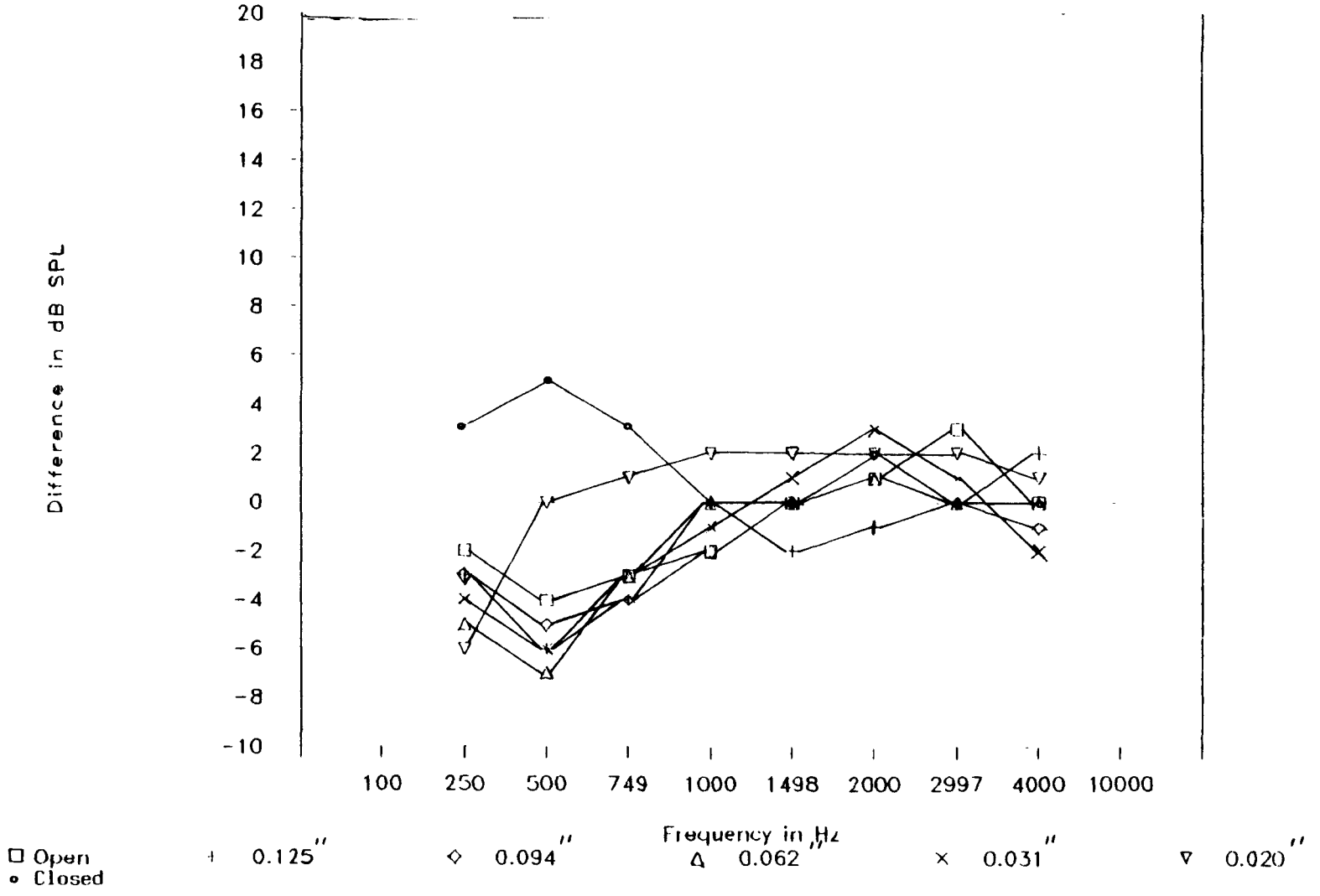

Figure 7. Differences in dB SPL between Condition A and B for subject 1. Negative data points indicate trials in which Condition B registered less gain than Condition A.

The results for subject 2, with the probe tube inserted through the special vent are shown in Figure 8. Again, as for subject 1, when this placement was measured, a decrease in insertion gain was measured for the occluded vent verses the open vent throughout the low to mid frequency region. This subject showed greater variability in measurements, particularly in the frequency range between 1000 and 2997 Hz. This variability in measurement did not appear to be a direct result of changes in SAV sizes.

The measurements obtained on subject 2 with the probe tube inserted between the earmold and ear canal are shown in Figure 9. An increase of 3-4 dB in insertion gain was noted as the SAV sizes progressed from the open to the occluded earmold. A similar trend was noted for subject 1 when this probe tube placement was measured. The results for subject 2 however, were more variable. In addition, they demonstrated differences in the insertion gain at specific frequencies which may not be a result of changes in SAV sizes, but rather may be due to variability with the instrument or measurement procedures.

A comparison of the insertion gain for subject 2 for the measurements obtained with the two different probe tube placement locations is shown in Figure 10. Differences up to 10 dB were noted between the measurements for most frequencies, which suggested that the two probe tube locations did not yield the same insertion gain results. Typically, for the lower frequencies a greater insertion gain was measured when the probe tube was inserted through the special vent. However, in the mid to high frequencies, the insertion gain was usually greater when the probe tube was between the earmold and ear

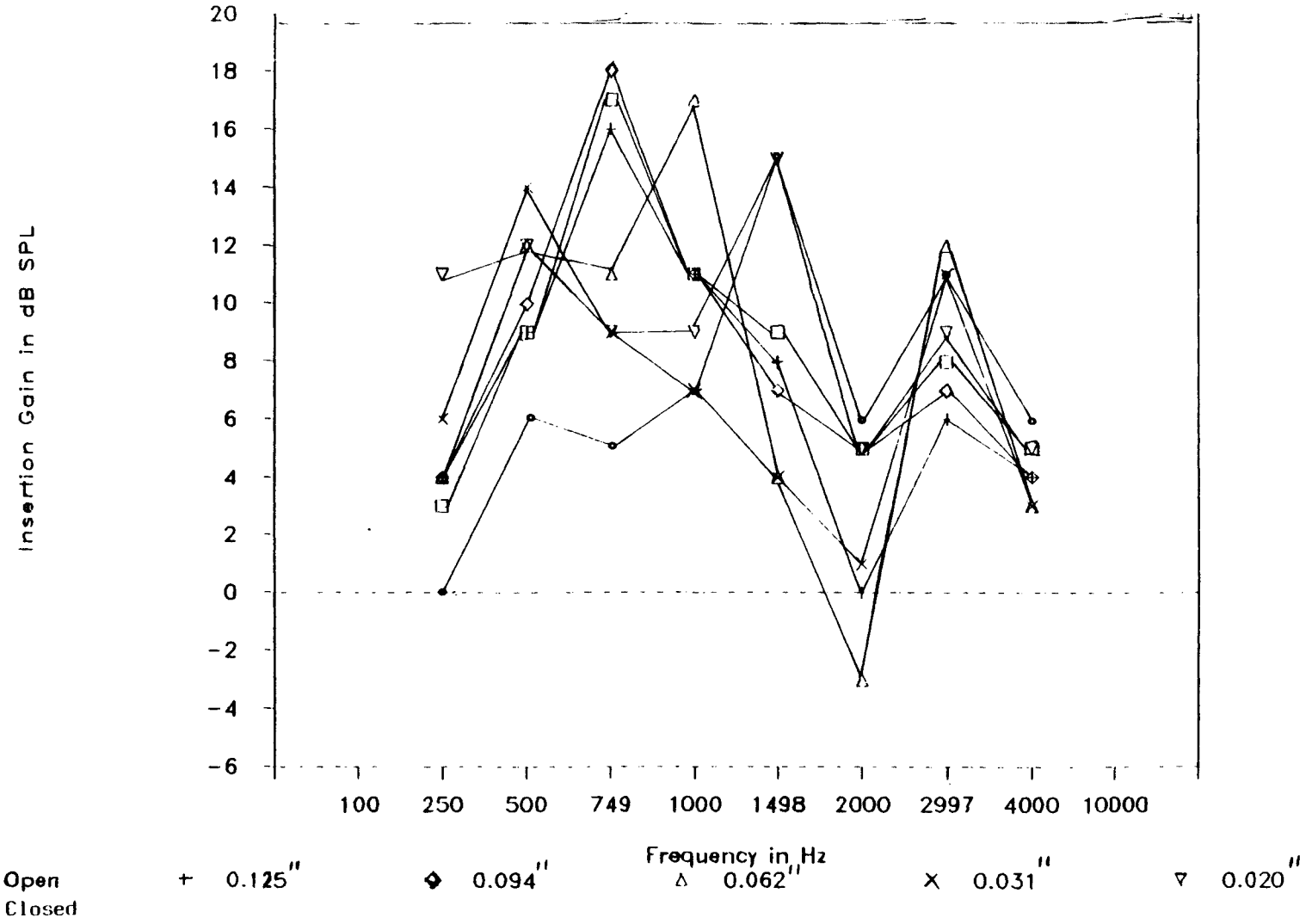

Figure 8. Insertion gain measured for subject 2 for each SAV size with the probe inserted through a special vent.

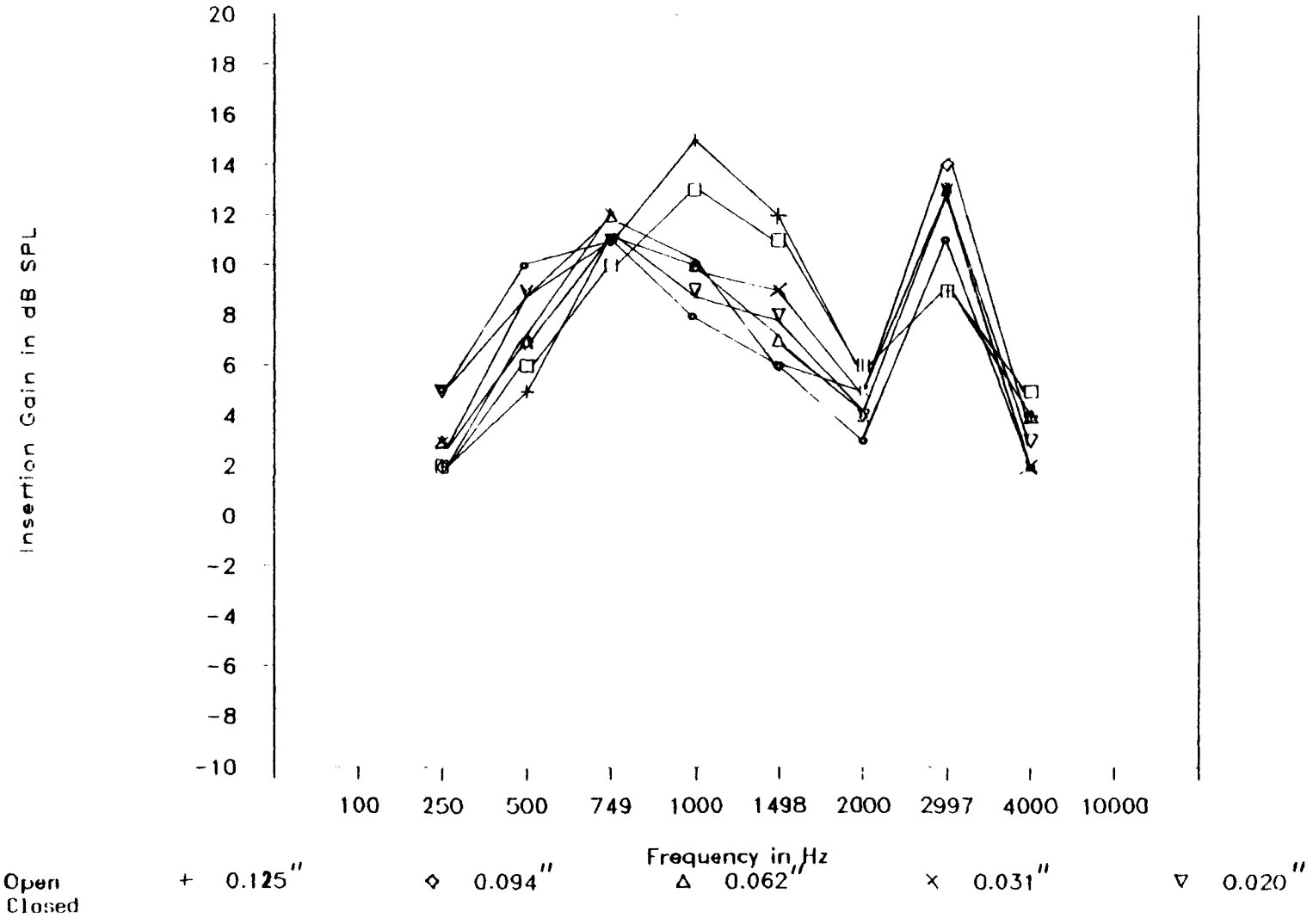

Figure 9. Insertion gain measured for subject 2 for each SAV size with the probe between earmold and ear canal

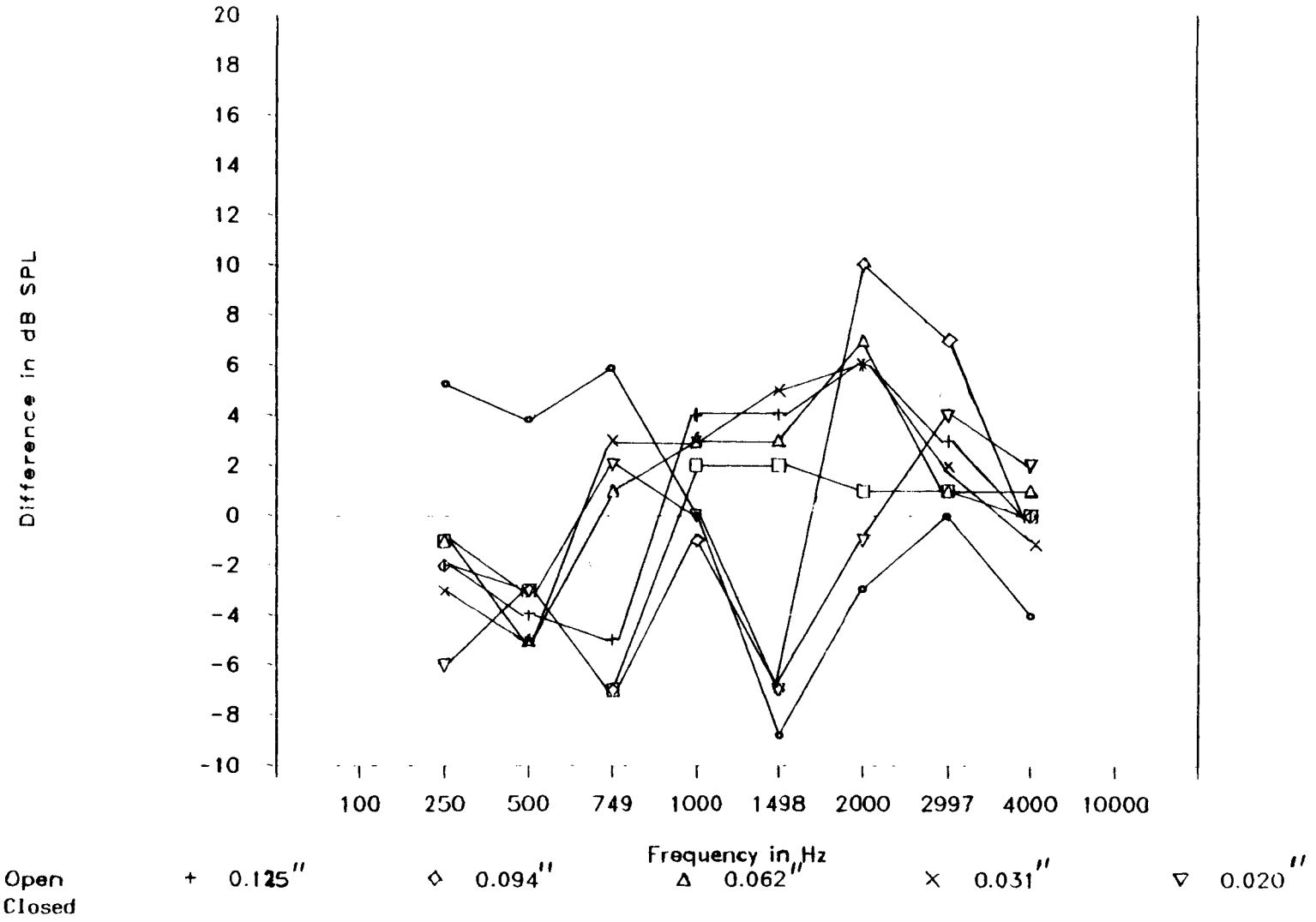

Figure 10. Differences in dB SPL between Condition A and B for subject 2. Negative data points indicate trials in which Condition B registered less gain than Condition A.

canal. These results were similar to those obtained on subject 1, however, subject 2 showed greater variability for all measurements. The inconsistencies in the measurements obtained prohibited detecting small acoustic differences in hearing aid output due to changes in SAV sizes. The differences observed for both subjects when the two different probe tube placement locations were tested demonstrated that equivalent results were not obtained between procedures, as has been suggested by the manufacturers.

Figure 11 compared the insertion gain measurements from both of the probe tube locations from subject 1 to the gain values measured electroacoustically by the FONIX 5500Z. Figure 12 shows the similar comparison for subject 2.

An examination of results for both subjects showed that the FONIX gain measurements were typically less than that measured on the CCI-10. Differences ranged from 3-9 dB at the lower frequencies. However, differences as great as 17 dB were noted between the CCI-10 measurements and the FONIX test box for the higher frequencies.

These two methods of estimating hearing aid output did not yield equivalent results. The large differences observed may suggest that the instruments did not measure similar functions and they did not result in comparable results.

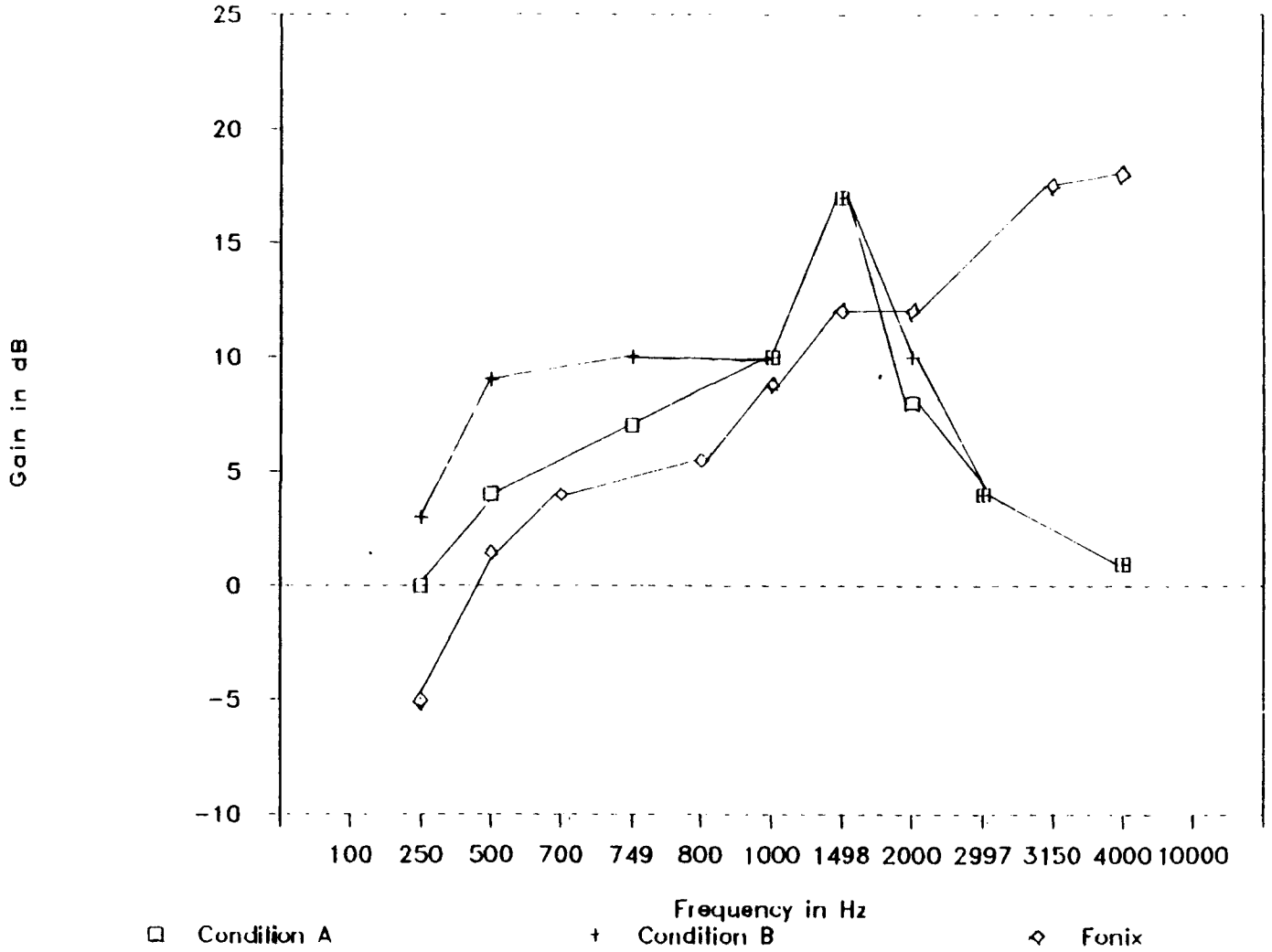

Figure 11. Comparisons of the differences in gain between Condition A, B, and the FONIX test box. Subject 1.

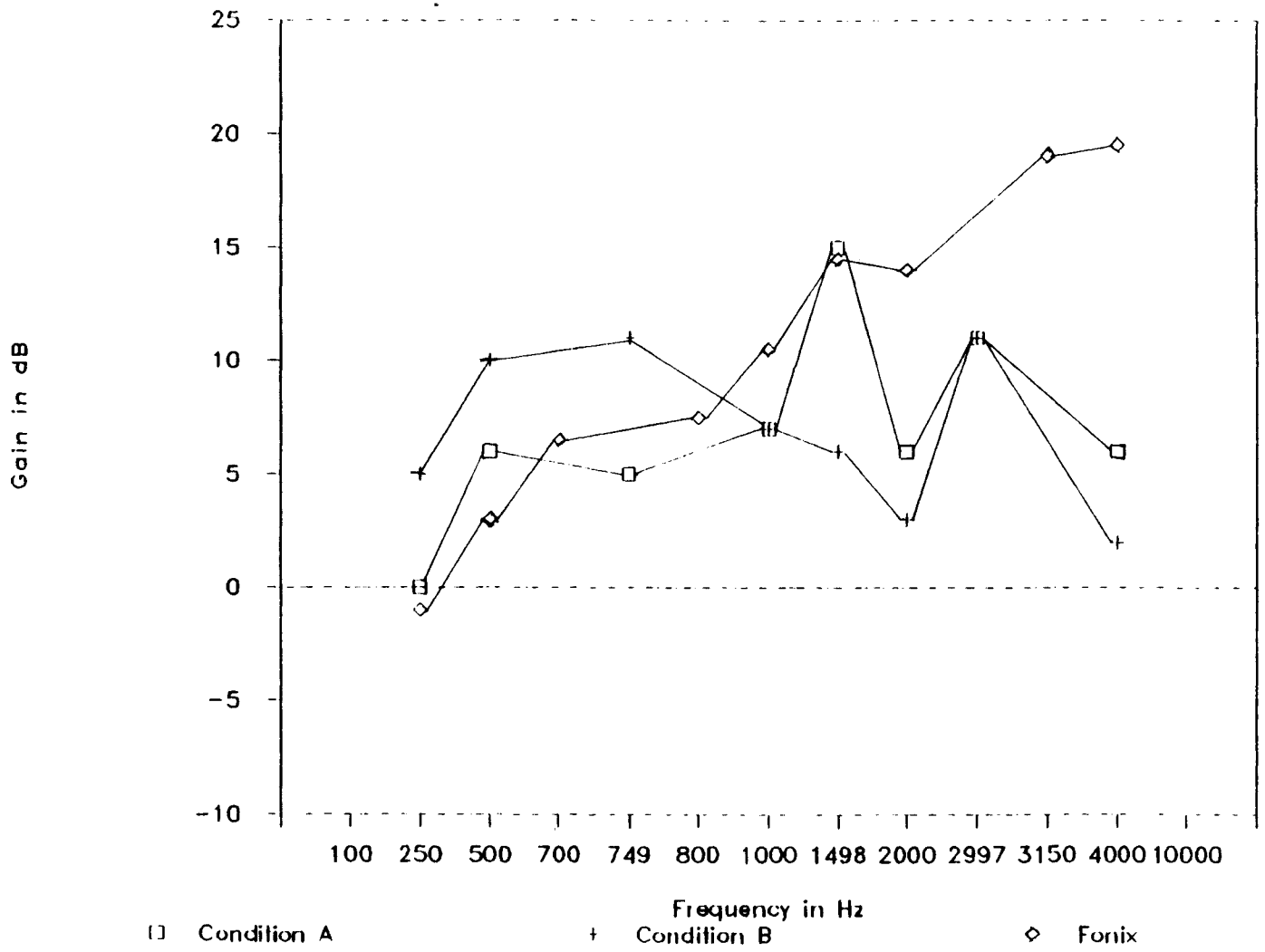

Figure 12. Comparisons of the differences in gain between Condition A, B, and the FONIX test box. Subject 2.

Chapter V: Discussion

The purpose of this paper was to investigate the reliability and accuracy of the CCI-10 Frequency Response Analyzer. Specifically, the hypothesis stated that if the CCI-10 was a reliable instrument, then small acoustic changes caused by different select-a-vent insert plugs could be measured. In addition, this paper investigated whether two different probe tube placement locations would yield essentially equivalent results.

The ability of the CCI-10 to maintain an 80 dB ($\pm$ 1 dB) signal throughout the frequency range appeared to be accurate when the CCI-10 results were examined in isolation. However, when these results were compared to independent measurements on a sound level meter, the results appeared to be less accurate and consistent. Hawkins and Mueller (1986) reported better agreement between instruments than those observed in this study. These differences between the two studies may be due to variability between instruments and also differences in the measurement procedures.

A comparison of the frequency response curves obtained when two different probe tubes were measured resulted in differences up to 5 dB at some frequencies. The exact reason for this discrepency was not known. The difference may have been attributed to differences in the resonance characteristics of the probe tubes, variability within the equipment itself, or a combination of these two factors. While the exact reason for this variability was not identified, the clinical implications warrant a caution to the hearing aid examiner. The

instrument's use in the clinical setting would necessitate interchangeable probe tubes. However, if the probe tubes do not result in similar responses, small acoustic changes may be interpreted inaccurately.

The data from measurements obtained with the probe tube placed in two different locations (through a special vent in the earmold and between the earmold and the ear canal) yielded some unexpected findings. Differences were noted to occur across both subjects when the two probe tube locations were compared. In other words, different clinical conclusions may have been drawn depending upon the probe tube placement location utilized. The data did not demonstrate the anticipated result of greater insertion gain in the lower frequencies as the SAV insert plugs were decreased in size. In fact, the exact opposite result was observed for some measurements. Finally, inconsistent changes in insertion gain were noted at frequencies which should not be effected by SAVs. These inconsistencies in measurements precluded drawing any conclusions about the acoustic changes which may have resulted from the alterations in SAV insert plugs.

A comparison between the CCI-10 and the FONIX hearing aid test box showed notable different results. The greatest discrepencies between the measurement instruments occurred in the higher frequencies, where differences as great as 17 dB were measured.

Since the work of Wiener and Ross (1946), many researchers have sought a means to measure hearing aid insertion gain through the use of probe tube measurements. Recent advancements in technology have made such instrumentation available and convenient for clinical use.

The CCI-10 is currently used in a variety of clinics, however the exact extent of its use has not yet been reported. The appealing aspect of this instrument is that the clinician can obtain ear canal measurements in a very short period of time. Conceivably, these measurements could be obtained on a variety of hearing aids as well as across a variety of electroacoustical modifications. Despite this appeal, and some of the reported, apparent advantages over other hearing aid fitting procedures, the question of the instrument's reliability and ability to detect small acoustical changes must be addressed further.

The integration of such a measurement device into the routine clinical procedure must be contingent upon the instrument's proven validity and reliability in the research environment. The sound level meter has been recognized as a highly accurate and reliable measurement instrument. Given the widespread use and acceptance of the sound level meter, comparative measures between the two instruments would be the most reliable type of measurement to verify output. The manufacturers of the CCI-10 have indicated that through the use of a self calibrating probe microphone system, a constant 80 SPL dB signal is maintained throughout the frequency range. Exactly how this was determined has not been reported in the literature at this time. Until adequate evidence exists which supports the reliability of the CCI-10 to produce a constant 80 dB signal, the usefulness of the equipment is severely limited. In addition, if variations in SPL are indeed occurring (as was the case in this study), equipment modifications should be made which would allow the

CCI-10 to detect and record these small changes. Comparative measurements of SPL on the CCI-10 and on an independent sound level meter should be undertaken on each device used clinically until its reliability has been clearly demonstrated.

Historically, the placement of the probe tube for ear canal measurements has either been through an already existing vent or through a specially designed vent for the probe tube. There are several limitations to such placements. The use of an already vented earmold prevents its application with high gain hearing aids because a vent may not be used due to feedback problems. Secondly, the size of the ear canal must be adequate to accommodate a vent (Pedersen 1982).

The placement of the probe tube between the earmold and ear canal has eliminated the necessity of a vent and also makes measurements of in the ear hearing aids possible. In addition, this procedure allows hearing aid measurement and fitting to be obtained using the same earmold clinically which may be worn on a daily basis by the hearing aid user. Comparative measurements which have focused on the differences between probe tube placement location have not been adequately investigated. The manufacturers of the CCI-10 have recommended that the probe tube should be inserted between the ear canal and the earmold, but they have not provided evidence which clearly show equivalent results between similar placement locations.

Pedersen (1982) compared the insertion gain measured with the probe tube placed in the same two locations as was used in this study. In seven of eleven subjects, the results were not equivalent in the frequency range below 500 Hz. These differences showed a reduction in

the insertion gain when the probe was placed between the earmold and ear canal. Pedersen also obtained measurements with an occluded earmold, whereas the present study compared different SAV sizes, as well as an occluded earmold. A comparison of the results obtained from these two studies with the earmold occluded, did not result in similar findings. In this study, the insertion gain measurements (for the occluded condition) showed slightly greater insertion gain when the probe tube was inserted between the earmold and ear canal for the lower frequency range. This was in contrast to other vent sizes measured. Typically, the insertion gain was less when the probe tube was placed between the earmold and ear canal. These results were also inconsistent and did not support the notion that a low frequency leak (caused by the location of the probe tube between the earmold and ear canal) occurred in a consistent and predictible manner. In addition, Pedersen reported equivalent measurements between the two probe tube locations for frequencies above 500 Hz. In the present study, a large variability between the two measurements occurred throughout the mid and high frequencies. These variations cannot be explained by the small changes in SAV insert plugs or by the possible effects of a base leak between the earmold and ear canal.

Based upon the results of this study, the two probe tube placement sites did not result in equivalent measurements. Despite the recommendations from the manufacturers of the CCI-10 that the probe tube should be placed between the earmold and ear canal for clinical use, these results suggested that further comparative measurements are necessary in order to determine the exact effect of

probe tube placement on measurements obtained.

Refinement of the procedure for the insertion of the probe tube needs to also include a comparison of probe tube insertion depth as this may be a contributing factor to the variations shown in the measurements of the two probe tube locations. Although this study did not specifically address the depth of insertion of the probe tube, the importance of this factor is recognized. An examination of the probe tube insertion procedures has indicated that measurements referred to as eardrum SPL have not been limited only to those obtained at the eardrum. Measurements have included those obtained at various distances from the eardrum in the ear canal. In order to precisely demonstrate the comparability of the two probe tube placement locations, measured in this study, it would be recommended that the probe insertion depth be specified and remain constant for both conditions.

The direct measurement of hearing aid and earmold modifications on the hearing aid user should offer the hearing aid specialist the opportunity to view the immediate effects of the changes in the frequency response. Various modifications through the use of vents, changes in tubing size and length, and dampers reported by Cox (1979) are used to create measureable electroacoustical changes in hearing aid output. The opportunity to measure these changes on the client must be viewed as an improvement in the prediction of the possible outcomes. However, because only small acoustical changes may result from these modifications, any measurement instrument must be capable of detecting these small changes. In addition, the instrument must

also be capable of reliable and repeatible measurements in order to make comparisons meaningful. The present results could not identify any clear effects of the different SAV plug inserts. The expected changes in SPL as a result of different SAV plug sizes had been observed to occur in the low frequency range, Cox (1979). Regardless of the size of the vent plug tested, measurements in the mid and higher frequencies have been observed to remain essentially unchanged. These observations were not substaintiated in this study. For both sugjects, the inconsistancies in SPL throughout the entire frequency range prevented the identification of specific vent associated changes. Therefore, the stated advantage of this instrument to measure small acoustical changes was not realized in this study. No clinical implications regarding the effect of different SAV insert plugs could therefore have been drawn.

VI: SUMMARY

In summary, the measurements of SPL obtained from an independent sound level meter showed some discrepencies with similar measurements for the CCI-10. The need for a valid measurement and calibration procedure with the CCI-10 is apparent. Efforts should be made to insure the accuracy of the instrument prior to measuring hearing aid insertion gain. The small variations in SPL were typical of the small changes expected as a result of changes in SAV plug inserts, as well as other types of earmold modifications.

The different probe tube placement locations also did not result in equivalent results across measurements. The interaction of the probe tube placement and changes in SPL as a result of SAV plug insert changes was not clear. This observation supports the need for continued research and a precise procedure for obtaining measurements in order to make the CCI-10 a clinically useful instrument.

The use of an instrument such as the CCI-10 in hearing aid selection and fitting offers the potential of identifying more closely what the hearing aid user actually hears. However, the lack of reported research on this instrument and the results of this study suggest that clinical implementation is still premature. This finding is important because the CCI-10 is being used in a variety of clinical settings at the present time. Exactly how the results have been interpreted and used has not yet been reported.

In addition to the specific problems noted in this study, future research should also include a thorough investigation of each procedural step as recommended by the manufacturer. Finally, the

effects of room acoustics, subject placement, speaker placement, and the influence of middle ear conditions on measurements should be thoroughly studied. Various possible sources of error and their interactions must be evaluated in depth in the research environment before this instrument can be successfully applied clinically. The results of this study have simply identified a few of the problems associated with this instrument.

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Appendix A

Rastronics CCI-10 Technical Specifications

Audio output:	>4 W RMS-8 ohm
Frequency range:	125 Hz to 8k Hz in 144 steps
Keyboard functions:	Cursor control Plot function Manual Frequency Control Pure tone Wobler tone ± 100 Hz at freq 25 Hz
Compressor:	>60 dB
Max. SPL:	Probe microphone: 130 dB Reference microphone: 120 dB
Sweep speed:	<20 seconds from 25 Hz to 8k Hz 3 curves can be displayed simultaneously
Accuracy of measurement:	± 1 dB
Distortion:	<1%
Time for calculation and display of insertion gain:	500 msec

Software controlled 120 dB attenuator with 1 dB resolution

Video output

Technical specifications provided by Rastronics ApS. US representation: Bernafon, Inc. 1299 U.S. Route 22 East, Mountainside, N.J. 07092

Appendix B

Measurement Procedures

1. The Rastronic speaker was suspended from the ceiling so that it was level with the subject's ear at a 0 azimuth.
2. The subject was seated approximately 1 meter from the speaker.
3. The microphone assembly was hung from the subject's pinna using the wire loop provided.
4. The examiner stood to the side of the subject and held the probe tube tip 1/4" from the opening to the probe microphone.
5. The computer keyboard function "Probe Calibrate" was pressed. Curve B (Figure B.1) was generated.
6. The keyboard function "Start" was pressed to obtain an 80 dB SPL ("Calibrated") signal in the probe tip circutry. Curve A (Figure B.1) was generated. According to the manufacturer, this "equalizes" the probe microphone circuit so that a constant output is maintained throughout the frequency range and a flat response is observed on the CRT.
7. The keyboard function "Manual Frequency Control" was pressed and the 80 dB SPL signal was adjusted to 70 SPL dB. This was done to avoid subject discomfort, since both subjects had normal hearing. (The CCI-10 can generate a 60, 70, or 80 dB SPL signal).
8. The probe tube was inserted approximately 18 mm into the external auditory canal.

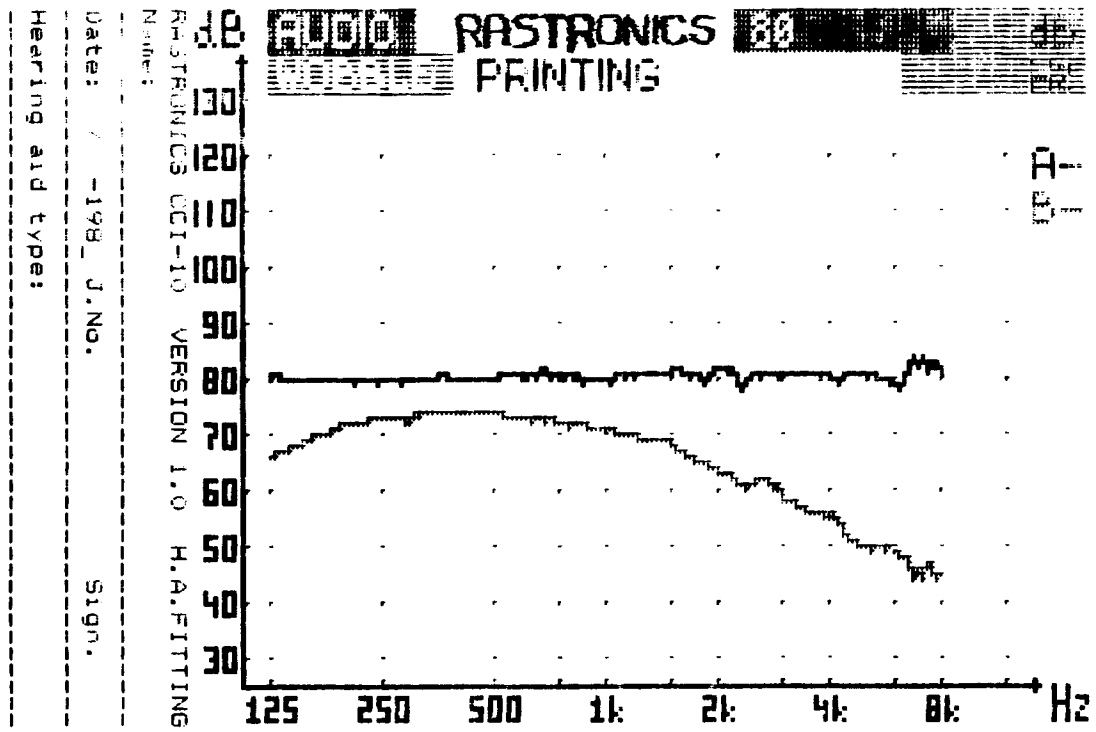

Figure B.1. Curve B (bottom curve) represents the initial sound field frequency response curve. Curve A (top curve) represents the 80 dB ± 1 dB) "calibrated" signal.

9. The keyboard function "Probe Calibrate" was pressed to obtain a measurement of the subject's ear canal resonance curve. Curve B, (Figure B.2).
10. The keyboard function "Start" was pressed and the ear canal resonance curve was automatically subtracted, which resulted in a flat frequency response showing no gain. Curve A (Figure B.2).
11. The probe tube was then inserted through the special vent in the earmold. The earmold was coupled to the hearing aid and was then inserted. The probe tube extended approximately 2 mm beyond the tip of the earmold. This condition has been referred to as Condition A in this study.
12. The keyboard function "Manual Frequency Control" was pressed, and adjustments were made using the hearing aid volume control to provide 12 dB of gain at 1000 Hz. The SAV was completely unoccluded for this initial measurement.
13. The keyboard function "Start" was pressed to obtain the "true insertion gain" throughout the frequency range. True insertion gain has been described by Rasmussen (1984) as being representative of the hearing aid's "etymotic" frequency characteristics after subtraction of the auditory meatus resonance.
14. Measurements were obtained for all SAV insert plug sizes, progressing from the unoccluded to the occluded earmold. SAV insert plugs were removed and replaced with tweezers in order to prevent a change in position in either the earmold

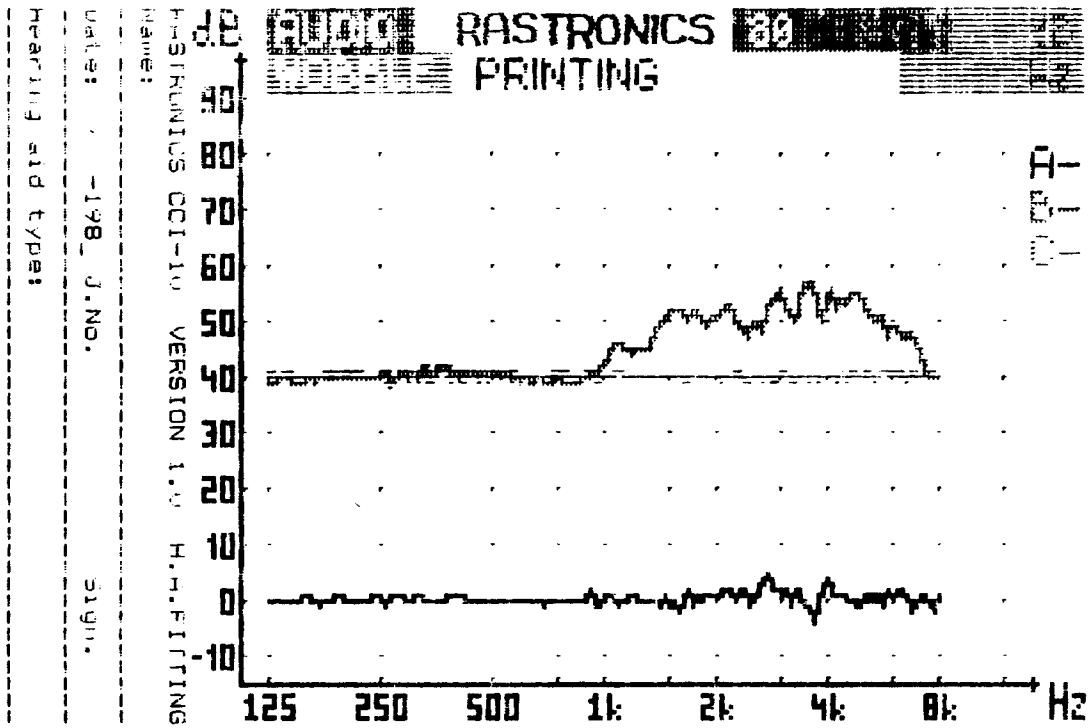

Figure B. 2. Curve A (bottom curve) represents the calibrated sound field. Curve B (top curve) represents the individual's ear canal resonance curve. Curve C (middle curve) represents the "flattened" frequency response curve. This is obtained by subtracting out the ear canal resonance.

or probe tube. The frequency response curves were obtained by pressing keyboard function "Start" for each of the SAV inserts.

15. Measurements for Condition B were obtained by inserting the probe tube between the earmold and ear canal. Again, the probe tube extended approximately 2 mm beyond the tip of the earmold. The small vent that had been used for previous insertion of the probe tube was occluded at its medial opening. Measurements for Condition B were systematically obtained in the same manner as described for Condition A.